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Ground-Based Demonstration of Imaging Fourier Transform Spectrometry and Techniques

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Abstract. We present results from a four-port Michelson interferometer built to demonstrate imaging Fourier transform spectroscopy for astronomical applications.

1. Introduction

NGST is designed to be an eight meter visible/IR astronomical telescope orbiting far from the radiation of Earth. NGST's instrument module must be matched to the satellite's unique aperture and orbit: this experiment must deliver wide field imaging and high resolution spectroscopy at high throughput. NGST alone will be able to observe to much fainter limits in the visible and infrared bands, revealing (currently unseen) sources in the high- z universe, and (currently) dark matter, as well as the faintest and smallest details of known objects. The spatial distribution and spectral signatures of the most interesting unseen objects are not well-known, and so a spectrograph of flexible resolution that obtains simultaneous spectra of the greatest number of objects across the telescope's focal plane must be one of NGST's science instrument.

An imaging Fourier transform spectrograph (IFTS) obtains a spectrum for every pixel in an imaged field, is highly efficient, and has the flexibility to choose the spectral resolution for any given observation. We represent the group proposing IFIRS, an IFTS for NGST (Graham *et al.* 1998), as the best solution for simultaneous efficient wide field imaging and spectroscopy.

The instrumental set-up for an IFTS is a four-port (two input ports and two output ports) interferometer. An image made at a focal plane is collimated and passed into one input port of the interferometer, the light is split into two beams by a beamsplitter, bounced through two arms and recombined, and at each output port the light is refocused onto an array detector. The moving arm of the interferometer is scanned through a series of optical path differences (OPDs), and for each OPD an image is obtained at each output port. The two series of images form two datacubes, with an interferogram at each imaged pixel. The nature of the two output datacubes is such that either each datacube can be transformed into a spectral datacube and co-added, or the two can be combined into one interferogram and then transformed. One can tune the spectral resolution using $\mathcal{R} = L/\lambda$, where $L = N\Delta L$ is the full travel of the moving arm, ΔL is the length of one step of the moving arm, and N is the number of steps.

Livermore National Lab has made great strides in the field of remote sensing imaging FTS, using 128×128 pixel cameras operating in the extremely high

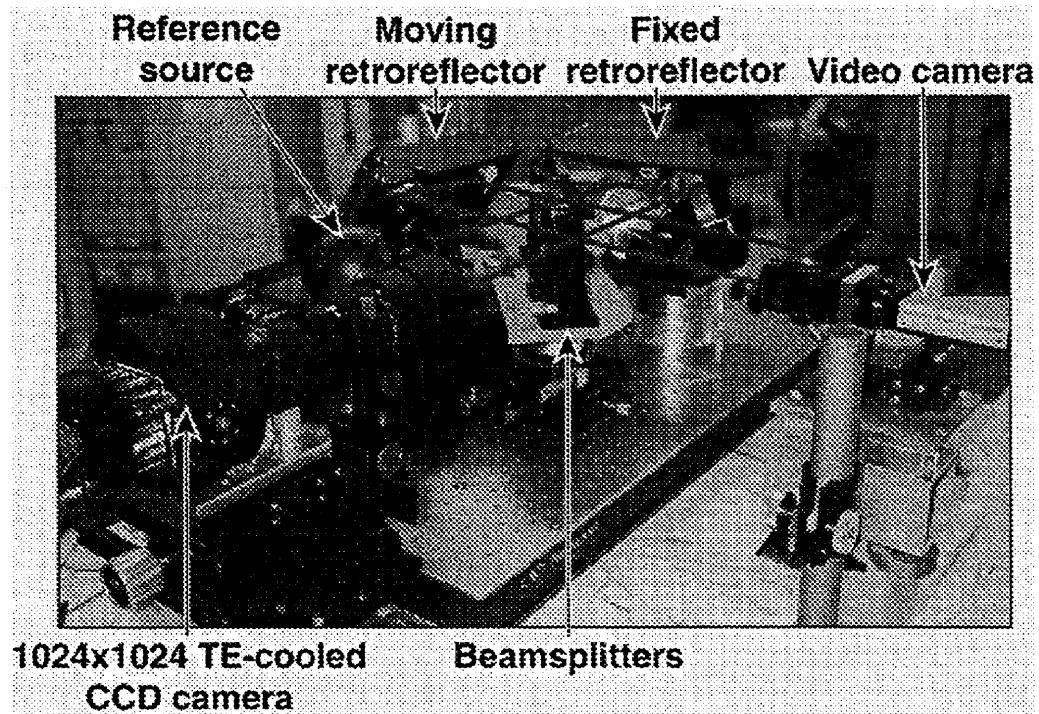


Figure 1. The ground-based instrument at MPSO. The grey arrows represent the light path through the interferometer. One input beam is deflected from above by a mirror on the right. The other comes from the calibration sphere on the left. The output beams go to the two cameras. A metrology reference laser interferometer lays below and behind the imaging interferometer.

flux at mid-infrared, fielded aboard jittering aircraft (Bennett *et al.* 1995, Bennett 1997). The datacubes, obtained in a few seconds, are typically 1024–8192 frames long and are reduced in a straightforward way using Fourier transforms. The IFIRS team needed to demonstrate IFTS under the expected NGST observing conditions and using realistic data reduction using real astronomical fields, because the techniques should be shown to work on astronomical objects, i.e. background-limited observations, unresolved objects, faint extended objects, extended regions, crowded fields, etc. The datacubes should reflect the NGST detector sizes, expected to be of order 1000×1000 pixels. The noise regime of NGST broad-band IFTS will generally be background-dominated, and the source and background fluxes will be low, meaning that the integration times will be long. Appropriate opto-mechanical demonstrations at these long dwell times can only be performed in background-limited low flux observations. For those reasons, the most accessible good match to test NGST near- and mid-infrared IFTS is ground-based visible astronomy, and so that is what we chose to do in the initial phases.

2. Testbed IFTS Instrument Description

The IFIRS study describes a four-port Michelson interferometer (Graham *et al.* 1999). Between the telescope focal plane and the input port there is a collimator so that light travelling through the interferometer is a collimated beam. To maximize étendue, the pupil (image of the primary) falls on the retroreflectors halfway between the two meetings with the beamsplitter. The second input port is used for calibration. Each output port is re-imaged onto a separate detector. Because the flux is low, this interferometer must stepscan, holding each step for a period of at least a few seconds.

The ground-based visible astronomical testbed does not stray far from the proposed IFIRS design (Figure 1). For many observations, the second output port was not used to obtain science data, but to monitor the field with a guide camera. Aside from that, the design used cube-corner retroreflectors, two opposed 75mm diameter beamsplitters for the two beams in compensated mode (no phase dispersion as would be introduced by unequal numbers of passes through the beamsplitter for each split path), and sometimes included a prism before the final camera lens to disperse the image, as an objective prism would. The moving arm sits on a 1-D motion stage whose positional accuracy of 20nm is typical of that required in the semiconductor industry. The path difference between the two arms is servo-controlled using a laser interferometer mounted on the same optical breadboard but offset approximately 25 centimeters from the center of the science beam. The design calls for two 1024×1024 $24\mu\text{m}$ pixel SITe back-illuminated TE-cooled CCD cameras at the two output ports. In the early stages, only one CCD camera was used.

This instrument was designed, built, and operated in the lab for a few weeks prior to its first observing run at a telescope. The fact that the system was then disassembled, crated, shipped, and re-assembled on the spectrograph bench at the McMath-Pierce Solar Observatory (MPSO) on Kitt Peak demonstrated the design's relative ease of alignment. We chose MPSO for our first run because this 1.5m heliostat-style telescope features the ability to deliver a derotated field to a meter-sized benchtop instrument, and the staff is kindly willing to support experimental visitor instruments. The dome was open for 9 nights in mid-March 1999, though not generally under photometric conditions. The four-port configuration was not used at MPSO, instead we used one output for the science camera and one output for a field acquisition and guiding camera. The focus was placed upstream of a collimator to form the pupil between the two excursions through the beamsplitter. A camera lens re-imaged the field with a magnification factor that yielded a final pixel size of 0.45 arcsec. The unvignetted field of view was four arcminutes in diameter.

3. Multi-Object Datacube And Extraction

We acquired a field containing the south edge of the globular cluster M4 and obtained a series of 64 four second frames at an OPD stepsize of 80nm. The conditions were not photometric. We were not able to integrate our guiding camera output adequately to the MPSO guide system and so the M4 data were collected unguided. This induced a drift of approximately one-fifth of a pixel

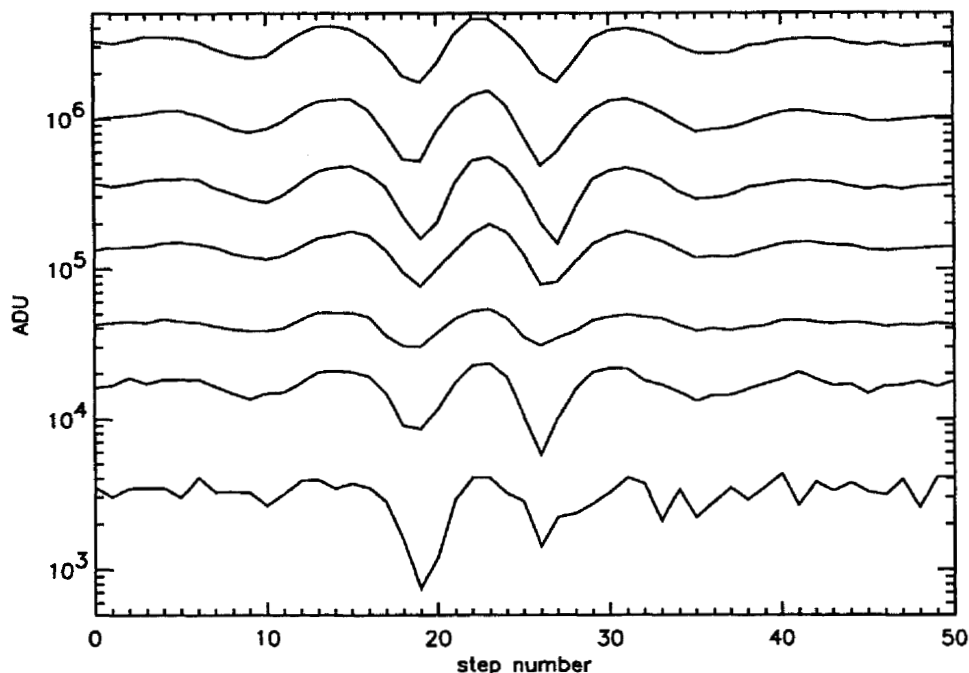


Figure 2. Representative interferograms of 7 of the 454 stars extracted using ALLFRAME from the M4 datacube.

per second. Seeing was measured at 1.8 arcseconds, which was good for this run. Because of the lack of baffling, large field of view, and lack of a true “dome”, we were unable to create a “dome flat” during the run. Instead a flat field derived from series of sky flats obtained on other nights was computed and used. In summary, these observations were not made under perfect conditions.

Nevertheless, we performed the usual reductions on the series of frames using iraf ccdproc routines, including overscan, zero subtraction, and flat-fielding, to obtain a set of images corresponding to known OPD values. Each image required these procedures prior to computing the Fourier transform. In order to obtain a deep panchromatic image by coadding the datacube, the frames needed to be re-registered because of the drift. Individual stars’ interferograms (Figure 2) were extracted from non-re-registered frames using ALLFRAME (Stetson 1994), a data reduction package developed for extracting multiple objects from series of frames obtained with a series of narrow filters, i.e. in the spectral as opposed to interferometric domain. This procedure estimates the intensity of each star at each OPD which is, in fact, the star’s interferogram. This would be the mode for extracting spectra of moving objects, *e.g.* Kuiper Belt objects, from deep NGST observations.

The interferograms appear to be clean, but the spectra are noisy. The main sources of noise were vibration and distortion of the relatively flexible structure holding the interferometer elements and the lack of photometric conditions. This particular demonstration was designed to investigate IFTS for low flux observa-

tions and we had not optimized the structural aspects of the device. The MPSO demonstration was also concerned with techniques for recovering information under non-photometric conditions, or more generally with time domain noise — time variable detector QE, dark current, and system throughput — and we address this topic in the following section.

4. Advantage of 4-Port Configuration for Suppressing Time Domain Noise

The four-port design is appealing primarily because all photons are counted. This is a strong selling point when the instrument is compared with spectrographs with slit and grating losses, or filter imaging systems which reject all out-of-band photons. However, there is another advantage to placing science detectors at both output ports. Imagine that the apparent intensity of the interferogram is changing as a function of time while the apparent spectrum is constant. Such a variation can correspond to spectrally-independent time variation in the source itself, gain variation in the detector, or time variation in the transmissivity of the background or optical elements. The transformed spectrum will include features due to this modulation. In the event that there are two output ports, the noise introduced by common mode modulation can be removed directly by using as the interferogram the sum of the interferograms from two ports over their difference, known as the “visibility” (Born & Wolf 1980, section 7.3.4), $(I_a - I_b)/(I_a + I_b)$. This procedure assumes a constant true flux and normalizes observations at each OPD to detected flux.

We simulated this time-induced noise in the lab by directing the light of Polaris through an open window and through the interferometer and took 0.1 second images through a 75 mm aperture so that we would observe scintillation from the atmosphere. We placed mirrors in such a way that each output port fell on different regions of the same detector. The resulting interferograms at each port separately show a S/N of 6, but the visibility has $S/N = 74$ (see Figure 3).

We expect that the visibility function will ameliorate potential common mode signal drifts in NGST data. These drifts may arise due to detector temperature variations or changes in scattered light from the sunshield. The two outputs also provide a direct method of identifying cosmic ray hits (Graham *et al.* 2000).

5. Dispersed FTS Existence Proof

A potential drawback of FT spectroscopy is that each spectral channel is subject to the shot noise from all the photons in the passband. This occurs because a single pixel counts all in-band photons in its interferometer arms at each interferogram frame. If for the same number of detected photons, the spectral resolution increases without a commensurate decrease in bandwidth, the noise in the continuum of an object eventually becomes unacceptably high (but emission line objects are specifically insensitive to this effect, Bennett *et al.* 2000).

One remedy for source noise limited observations is to disperse the image of the object across several, m , pixels using a low dispersion prism. For a single slice in the datacube, the image looks similar to that obtained through an objective

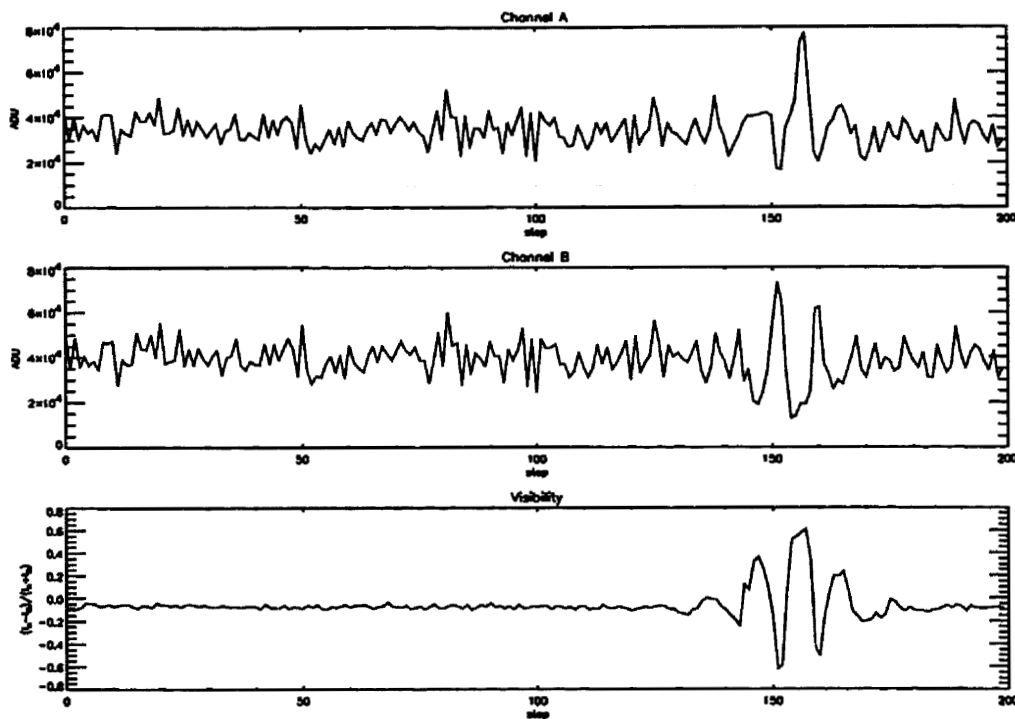


Figure 3. I_a, I_b , and visibility.

prism (though the trace is modulated sinusoidally at each OPD). Now each pixel sees a fraction of the spectrum, and for a flat spectrum object the shot noise goes down by the square root of m . The useable field of an M by M chip decreases by the factor $1 - (m/M)$. Interestingly, objects whose spectra overlap are separable in the transformed datacube, the spectra are no longer in the z -direction, but along a series of curving parallel paths given by the dispersion function of the prism and resolution of the FTS.

In Figure 4, we present a cut along the dispersed image of Polaris showing the interferogram for the subregion of the spectrum in each pixel. Next to it, we have Fourier transformed this cut to show the path of the star's spectrum through the datacube. The prism was of higher dispersion than one would select for a "true" hybrid FTS, but the method is shown to work with a real stellar source. An example program which would benefit from hybrid FTS observations is the high resolution observations of bright cluster giants where the sky and dark current background is negligible.

6. Simultaneous Narrowband Imaging

Finally, we present the results of an MPSO observation of a diffuse nebular region, M42, the Orion Nebula, to demonstrate a technique useful in a region featuring little thermal emission — we were able to do simultaneous imaging in multiple widely-separated emission lines. The technique sparsely samples a long



Figure 4. In the x-direction is the prism-dispersed spectrum of Polaris convolved through the optics and detector passband. In the y-direction on the left is the interferogram of each pixel, on the right is the spectrum for each pixel. In the configuration described for the NGST instrument, the dispersion in the prism would be lower than that in the FTS.

total optical path difference. The sparse sampling leads to a long OPD step-size, which produces a very low calculated Nyquist frequency, $f_{Ny} = 1/2\Delta L$, below the passband of the observation. The passband is aliased into the spectral channels of the Fourier transform of the observed interferogram (Griffiths & de Haseth 1986, chapter 16, section II). One can recover the intensities and line-shifts of lines of known frequency by computing the spectral channels corresponding to the in-passband frequencies. Under certain conditions of passband, stepsize, and total path length, the passband aliases are folded more than once through the computed spectral channels and several frequencies in the passband are thus aliased into a single spectral channel.

The M42 observation was performed using a collimator, beamsplitter, mirrors, camera lens, and CCD whose combined passband was approximately 450-950nm. We made 256 samples at an OPD of $0.8\mu m$, the Nyquist frequency of the observation was $6250cm^{-1}$ ($1.6\mu m$). There were 128 spectral channels in the transformed spectrum, the passband encompassed folded orders 2, 3, and 4. We computed the line center of $H\alpha$ and [OIII] and extracted the corresponding channels as slices from the spectral cube. In Figure 5, we use these two slices and a panchromatic slice to create a three color false color image of the nebula (red = $H\alpha$, green = [OIII], blue = continuum). We can clearly see the south-east ionization front — a wall of $H\alpha$ along the edge fading to greener [OIII] behind, and the stars are comparatively blue, as expected. Each of these slices is equivalent to a filter observation, two narrowband and one broad, but they were acquired simultaneously, with corresponding multiplex advantage.

7. Conclusion

This system helped us test opto-mechanical components and observational and computational techniques necessary for imaging spectroscopy of astronomical objects. These observations required holding positional stability to 10 nm over times of 1 – 10 seconds, and they required simple modifications to “usual” astronomical data handling methods. This project continues to demonstrate astronomical FTS observing in the low flux regime by breadboarding together technology and techniques. We now stand ready to incorporate developing NGST instrumentation into similar systems in order to advance the technology. We

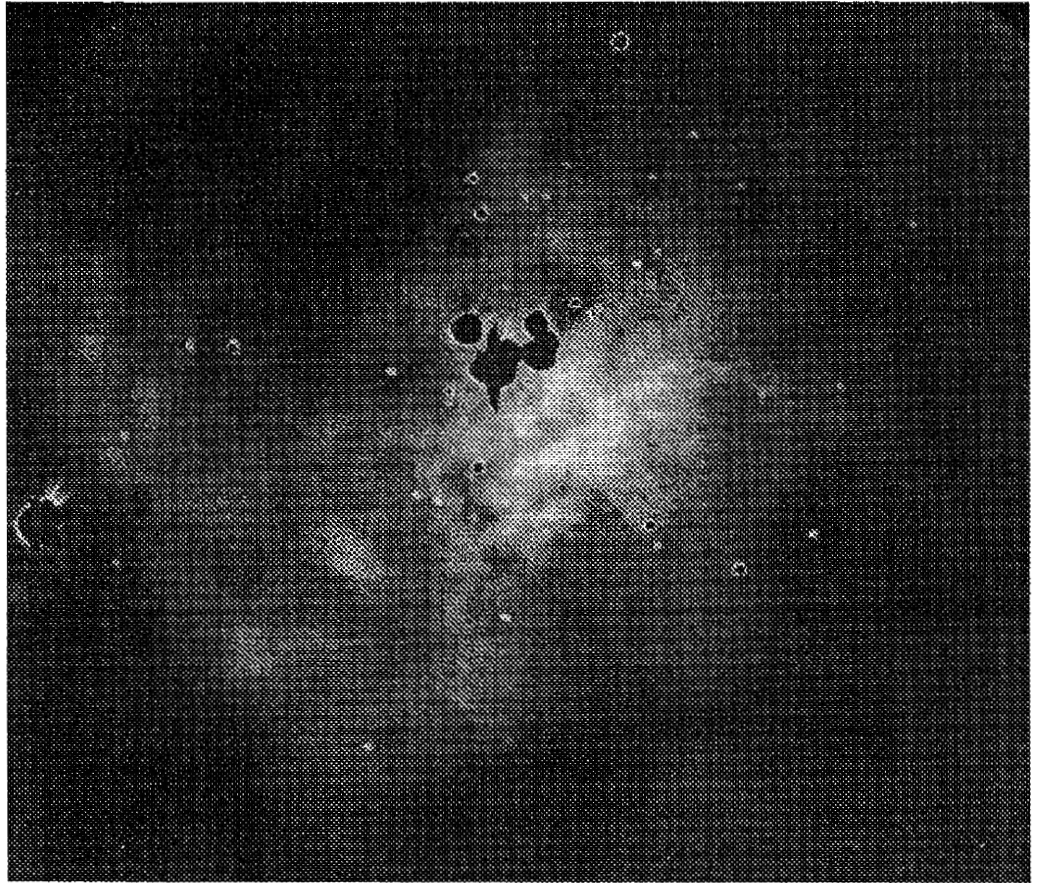


Figure 5. A color image of M42. red = $H\alpha$, green = [OIII], blue = continuum. Saturated star centers have been clipped out of this image.

are planning a facility-class ground-based optical IFTS, building a fieldable instrument around the interferometer provided by the Canadian component of the IFIRS team. Our long range plans include a similar mid-IR instrument for ground-based observing as well as for testing NGST cryogenic IR instrumentation.

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References

- Bennett, C. L., Carter, M. R. & Fields, D. J. 1995, Proc. SPIE, 2552, 274
- Bennett, C. L. 1997, Proc. SPIE, 3063, 174
- Bennett, C. L. *et al.* 2000, in prep.
- Born, M. & Wolf, E. 1980, "Principles of Optics", 6th ed. Cambridge University Press.
- Graham, J. R., *et al.* 1998, PASP, 110, 1205
- Graham, J.R. *et al.*,
http://ngst.gsfc.nasa.gov/public/configured/doc_547_1/NGST_ISIM_IFIRS.pdf
- Graham, J. R. *et al.* 2000, in prep.
- Griffiths, P.R. & de Haseth, J.A. 1986, "Fourier Transform Infrared Spectrometry", Wiley & Sons
- Stetson, P.B. 1994, PASP, 106, 250

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